Wave Breaking Influence in a Coupled Model of the Atmosphere-Ocean Wave Boundary Layers under Very High Wind Conditions

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Award #: N000140010288

LONG-TERM GOALS

The long-term goals are to contribute improvements in current physical understanding and modeling of interfacial processes fundamental to air-sea interaction fluxes, particularly those involving wave breaking and spray droplet production. These advances will improve the reliability of operational sea state and ocean weather forecasting models, particularly for severe to extreme sea states.

OBJECTIVES

This project seeks to improve the accuracy of air-sea interfacial flux parameterizations in coupled sea state/marine weather forecasting models, with a particular focus on refining and incorporating the role of wave breaking and sea spray in severe conditions. The approach adopted is to develop more realistic parameterizations for breaking occurrence and strength, and sea spray/spume source functions and validating them in test-bed models against observations. The end goal is implementing these improvements in a coupled COAMPS/WaveWatch III model for operational use.

APPROACH

Our approach is to build substantially on our accumulated expertise in sea surface processes and air-sea interaction (Banner) and numerical weather modelling (Leslie, Morison) to identify and close fundamental knowledge gaps in order to improve the modeling accuracy for severe marine meteorological events such as hurricanes. Such improvements depend critically on gaining a more complete understanding of severe sea state phenomena linked to wave breaking, due to their increased surface drag and allied air-sea flux enhancements, including sea spray production.

Quantifying the distribution of wave breaking events has progressed substantially within this project as a result of an intensive collaboration on breaking wave observations with D. Farmer and J. Gemmrich (IOS, Canada) in FY01, and more recently with J. Gemmrich (UVic, Canada). From their IOS storm wave datasets, a robust *threshold behavior* was identified for wave breaking at different scales in terms of the wave spectral saturation level $\sigma(f)$ (Banner et al, 2002, hereafter BGF02). The saturation $\sigma(f)$ is

Report Documentation Page

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1. REPORT DATE **30 SEP 2006**	2. REPORT TYPE	3. DATES COVERED **00-00-2006 to 00-00-2006**
4. TITLE AND SUBTITLE **Wave Breaking Influence in a Coupled Model of the Atmosphere-Ocean Wave Boundary Layers under Very High Wind Conditions**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of New South Wales,School of Mathematics,Sydney 2052, Australia,**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**14**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

given by $\sigma(f) = (2\pi)^4 f^5 F(f)/2g^2$, where F*(f)* is the wave energy spectrum and *f* is the frequency. This result has proven very useful in our ongoing effort to parameterize wave breaking spectrally in wind-wave models, and underpins our new spectral source term formulations for the wave energy dissipation rate. It is also being used in the spray/spume production term formulated in collaboration with C. Fairall (NOAA). More recently, Gemmrich has analyzed the evolving wave breaking properties of a developing strong wind sea event during the recent ONR-funded FAIRS experiment conducted in October 2000 from RV FLIP (please see http://airs.apl.washington.edu/projects/fairs/summary.htmlu) Model development in this project has focused on refining *full-bandwidth* computations of the directional wave spectrum and its tail region using an 'exact' version of the nonlinear wave-wave interaction source term in the radiative transfer equation for the wave field. We have concentrated on fetch-limited and duration-limited growth cases, since the bulk of observational data exists for these cases. This ensures that modeled spectral saturation levels (and dissipation rates) are consistent with observed levels, and allows predicting spectral breaking wave properties and hence enhanced air-sea fluxes associated with wave breaking. This information is needed to underpin future operational versions of coupled atmosphere-wave-ocean models.

We have focused strongly on formulating, implementing and refining modeling strategies for:
(a) extracting the relevant wave breaking parameters and (b) calculating wind stress/roughness length enhancements and updating the surface layer winds accordingly. For (a), we have significantly refined our previously reported capabilities for calculating the spectral density of mean breaking wave crest length/unit area. This is a primary goal of this project, as this quantity is central to the prediction of breaking wave enhancements to the wind stress, and development of a spray/spume source function based on sea state rather than the wind strength. To this end, further progress has been made in refining the form of S_{ds} proposed by Alves and Banner (2002) [hereafter AB02] and on advances in predicting wave breaking probabilities at different wave scales in BGF02. In particular, the AB02 form of S_{ds} was upgraded to incorporate the observed BGF02 breaking saturation threshold. Also, various refinements were introduced to its spectral distribution. This was done in order to provide a much better match to the wind input source function S_{in} at higher wavenumbers, and to recently published observations of the spectral density of breaking wave crest length/unit area. To progress, we have had to invest very considerable effort evaluating various versions of the wind input source terms S_{in}, and propagation schemes in the radiative transfer evolution equation, in order to ensure accuracy and minimise computational instabilities that can develop at higher wavenumbers.

During FY06, we focused on the issue of breaking wave properties at the spectral peak, and looked very carefully at the newly available data from the FAIRS experiment on how this changed as the wind sea aged (Gemmrich, 2005). Our model simulations examined carefully the complex relationship between the wind input and dissipation rate source terms. Special attention was also given to the 'holistic' issue of matching wind input to the *total* dissipation rate in the wave boundary layer.

WORK COMPLETED

During FY06 we continued our main effort on hurricane wind-wave model development, with explicit computation of wave breaking properties. Our capability for computing the directional wave spectrum was refined further, with particular emphasis on ensuring our modeling could reproduce observed breaking wave properties at the spectral peak, where the relationship between the breaker properties and the wave dissipation rate is best understood.

For this effort, attention was focused on the wind speed regime of U_{10} ~ 12 m/s which prevailed during FAIRS. We also ensured that our model was operational out to 60 m/s wind speeds, where the challenge was to achieve stable model behavior in the spectral tail region. We now await breaking wave data from other PIs within the CBLAST project to validate those very high wind speed results.

In our model-data comparisons, we examined a range of diagnostic properties: evolution of energy and spectral peak frequency, 1D transect wave spectra and spectral directional spreading. For the breaking data, we investigated breaking crest length spectra $\Lambda(c)$ (eg. Phillips, 1985), and used the observations of Phillips et al (2001), Melville and Matusov (2002) and Gemmrich (2005). For the directional spreading data, Hwang et al. (2000) provided the basis for our validation.

A state-of-the-art version of the 'exact' nonlinear source term S_{nl} (D. Resio, private communication) was used throughout this study to avoid known difficulties with approximate forms used in operational wave forecast models. Also, we decided to investigate a number of representative wind input source terms S_{in} as these can be seen to differ appreciably, especially in their different weighting across the spectrum. Figure 1 illustrates these differences for the S_{in} forms due to Janssen (1991) and Hsaio and Shemdin (1987). The large difference between these two forms for low U_{10}/c (long waves) and for high U_{10}/c (short waves) are apparent. This has strong implications when breaking properties are to be modeled successfully within the other constraints imposed by the observations. The historical data trends from Snyder et al (1981) for ocean waves with low U_{10}/c and Plant (1982) for short laboratory wind waves with high U_{10}/c are indicated in this figure for reference.

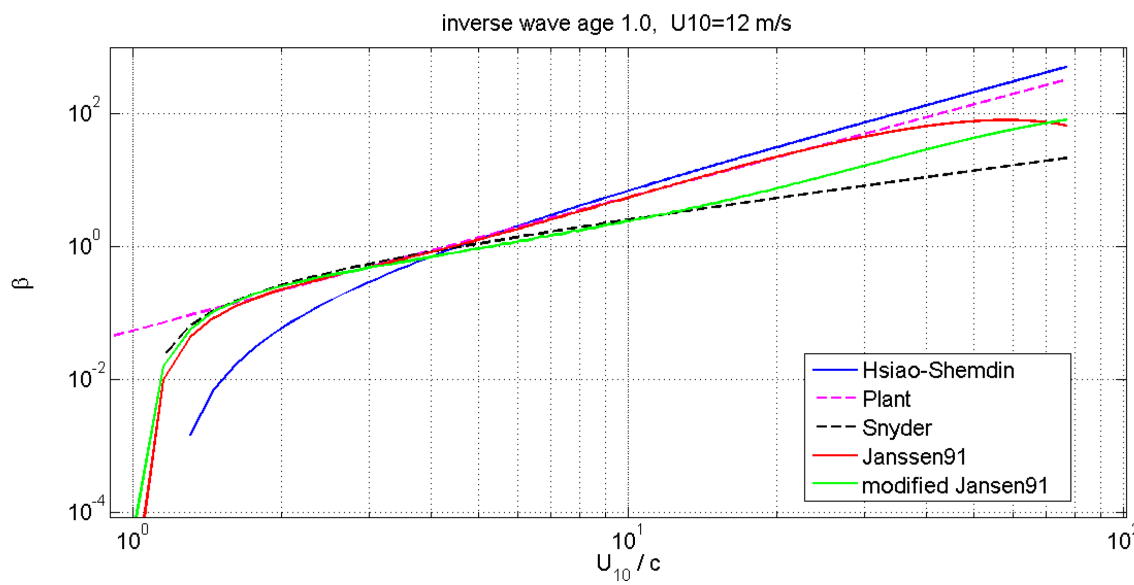

Figure 1. This logarithmic plot highlights the considerable differences between the spectral growth rate β of selected commonly implemented forms of S_{in} for maturing seas (U_{10}/c_p~1.0). The modified Janssen91 curve shows the extent of sheltering introduced for the slower moving, shorter wave components to bring the computed wind stress into agreement with observed levels.

Our spectral wave energy dissipation rate source term, S_{ds}, has a primary dependence on wave nonlinearity through its functional dependences on the spectral saturation (see AB02).

$$S_{ds}(k,\theta) = C\,[(\tilde{\sigma} - \tilde{\sigma}_T)/\tilde{\sigma}_T)^a\, \tilde{\sigma}^b + \varepsilon_{res}\,](\sigma/\sigma_m)^c\, \omega F(k,\theta) \quad (1)$$

Here σ and $\tilde{\sigma}$ are respectively the saturation and saturation normalized by the directional spreading width, $\tilde{\sigma}_T$ is threshold normalized saturation and σ_m is the saturation at k_m, the mean wavenumber at the transition from the peak enhancement region to the spectral tail. The breaking threshold switching exponent a was taken as 2, with b taken as 0 and c taken as 4, based on matching to the high wavenumber form of $S_{in}(k)$. The tuning constant C was chosen to provide the optimal match to observed duration evolution data of the spectral peak energy and peak frequency (eg. Young, 1999). ε_{res} is a small background residual dissipation coefficient that is consistent with observed decay rates of swell leaving storm areas.

The model performance was investigated by extensive computations of the evolution of the directional wave spectrum using the above source terms in the standard radiative transfer equation. We studied duration-limited evolution, over a wide bandwidth typically out to several Hz. As shown below, the model performed very well in reproducing a broad range of observational spectral properties.

With these diagnostic benchmarks satisfied, we proceeded to make extensive calculations of the spectral density of breaking crest length per unit area, and how these breaking wave spectra change with wind speed and wave age. It should be noted that the model computes the evolution of the spectral dissipation rate S_{ds}, and the precise link between S_{ds} and the spectral density of breaking crest length/unit area $\Lambda(c)$ is not well understood, and is a current research topic of considerable complexity.

The assumption that wave breaking dissipation is localized spectrally is not well-established, i.e. that spectral dissipation at scale c (or k) is only associated with breaking waves of that scale. It is most likely to be valid for the dominant (spectral peak) waves. Phillips (1985) proposed that if *localized* spectral dissipation is assumed, then $\Lambda(c)$ may be calculated from:

$$S_{ds}(c) = b\,(c^5/g)\,\Lambda(c) \quad (2)$$

The non-dimensional coefficient b reflects the strength of breaking, but its value, as well as its spectral dependence, cannot be derived from theory and needs to be assessed observationally. As there are no available direct measurements of spectral dissipation rate S_{ds}, the available field measurements of $\Lambda(c)$ of Gemmrich (2006) were used, where $b \sim 2\times10^{-5}$ was reported. We investigated whether our S_{ds} model provides a self-consistent and robust formulation under the localized spectral dissipation assumption (2). This is expected to be most applicable for the waves in the spectral peak region. Thus our primary goal was to determine whether (2) was able to reconcile observed and computed breaking crest length spectral density levels for the dominant waves. Our recent progress on this key aspect is described below under 'Results'.

For the shorter waves above the spectral peak, there are also *non-local* sources of dissipation, such as attenuation of short waves both by longer breaking waves and also through strong nonlinear interaction with non-breaking, steep longer waves. In strongly forced sea states (typical of hurricanes), these spectrally non-local effects are likely to be significant. We have already begun work on modeling these effects, which presents considerable challenge, and will seek to refine this during FY07.

RESULTS

Refinement of wind input and dissipation rate source terms – reconciliation with FAIRS Experiment breaking wave data

The breaking wave data used for our validation was gathered during the FAIRS experiment and reported in preliminary form by Gemmrich (2005). There were synchronous measurements of wind speed and direction, wind stress and wave height during the observational period. However, a unique feature of this data set was the measurement of wave breaking properties for a developing wind sea (U_{10}/c_p~1.2), in addition to those for mature sea conditions. Such data for growing wind seas was not previously available.

In this regard, there were noteworthy differences in the breaking probabilities between developing (U_{10}/c_p~1.2) and mature seas ($U_{10}/c_p<0.9$). The crucial feature evident for the developing seas is the significant breaking occurring at the *spectral peak* wave scales. According to all variants of the wind input source term, there is relatively low wind input to the spectral peak waves for U_{10}/c_p~1.2, yet the observations confirm the presence of dominant wave breaking, as measured by the breaker speeds. This presented a significant challenge for the model to reproduce.

The results for integral wave spectral properties, mean energy and peak frequency, achieved a close correspondence with observed evolution behavior in Young (1999), as seen in Figure 2 below. We also obtained very close model agreement, both level and spectral slope, with the high wavenumber tail of the 1-D transect spectrum observed by Melville and Matusov, 2002 (Figure 3). Modeled directional spreading properties compared very favorably with the data of Hwang et al. (2000) (Figure 4) and also with high wind speed results from the recent GOTEX experiment (Melville et al, 2005), in regard to both the bimodal shape at higher wavenumbers and the mean spreading width against wavenumber. Computed wind stress levels closely matched observational levels (Figure 5).

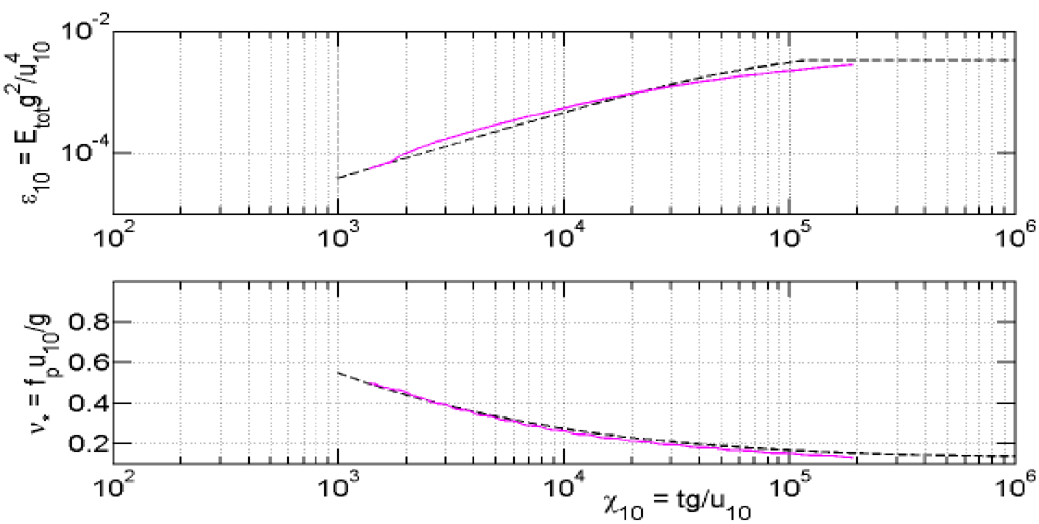

Figure 2. Evolution of the non-dimensional wave energy (upper panel) and non-dimensional dominant wave frequency (lower panel) against non-dimensional time. The background dashed curve is the trend of available field observations collated by Young (1999).

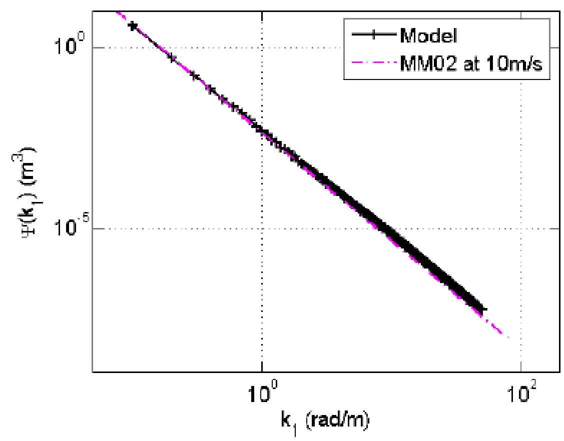

Figure 3. One-dimensional transect spectrum in the dominant wave (k_1) direction for mature seas, showing a k_1^{-3} behavior. The background curve was measured by Melville and Matusov (2002) for 7-13 m/s wind speeds.

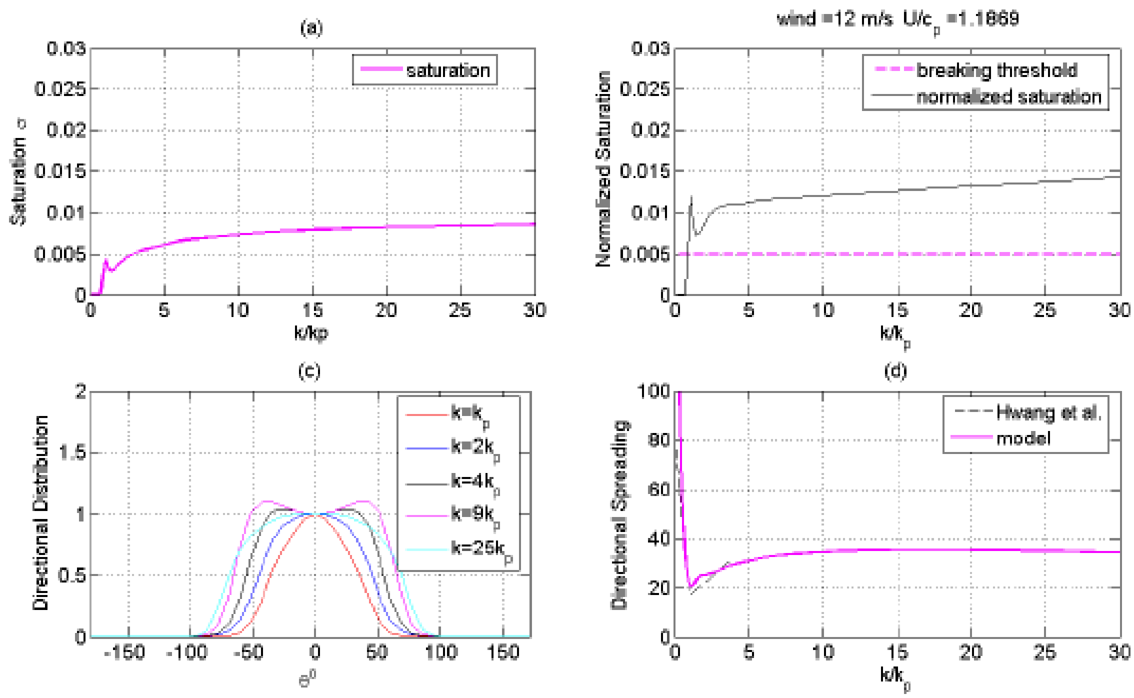

Figure 4. (a) azimuth-integrated spectral saturation against distance from the spectral peak wavenumber, for inverse wave age U_{10}/c_p ~1.1 (b) corresponding normalized saturation formed from (a) by division by the mean spreading width in radians (c) directional distribution of energy at different wavenumbers relative to the spectral peak. These agree with the observations reported in Figure 2 of Melville et al (2005) (d) variation with wavenumber of the mean spreading width in degrees, compared with observations reported by Hwang et al. (2000). The calculations match the observed peaked off-wind nature and strong broadening of the direction spreading towards the shorter wave scales reported in recent field studies.

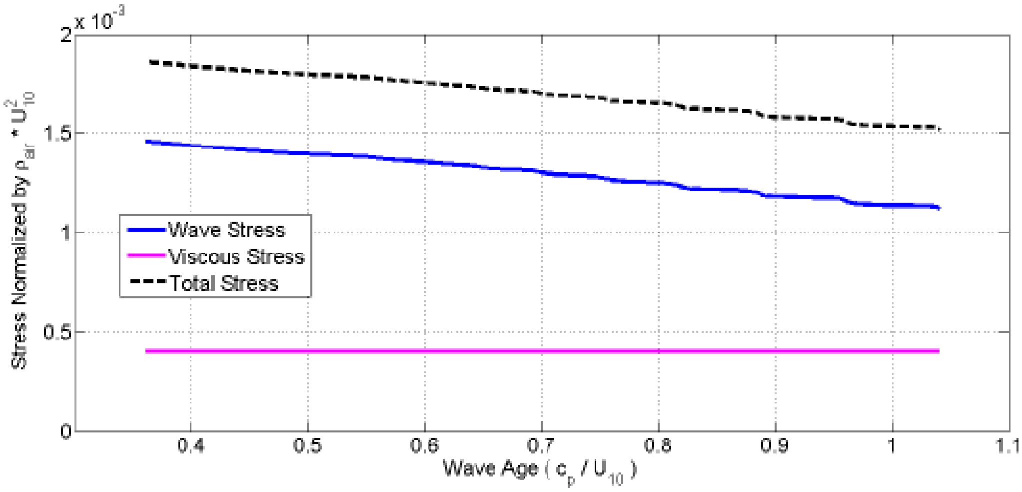

Figure 5. Evolution with wave age of the normalized total wind stress (the sea surface drag coefficient). The fully developed sea asymptotic value is very close to the observed level of 0.0014. The behavior of the normalized wave stress and viscous tangential stress components is shown the wind sea ages. The viscous stress follows the estimate by Banner and Peirson (1998).

Figures 6 and 7 show the modeled and observed spectral distributions of $\Lambda(c)$ for different wave ages. The behaviour at the spectral peaks of the developing seas (period 1 where c_{peak} = 10 m/s) and mature seas (period 3 where c_{peak}=12.5 m/s). These are the focus of the breaking forecasting validation.

A comparison of these observed and model results shows that the spectral peak level of $\Lambda(c)$ changes over an order of magnitude as the wave age c_p/U_{10} changes from 0.83 (period 1) to 0.96 (period 3). For the dominant waves, the results indicate very encouraging agreement between observed and forecast levels during both of these observational periods. Further comparisons with data are now needed to establish the robustness of the modeling approach used here. For the shorter waves, we note that model predictions are not in accord with the data, as foreshadowed above, and will be the investigated further.

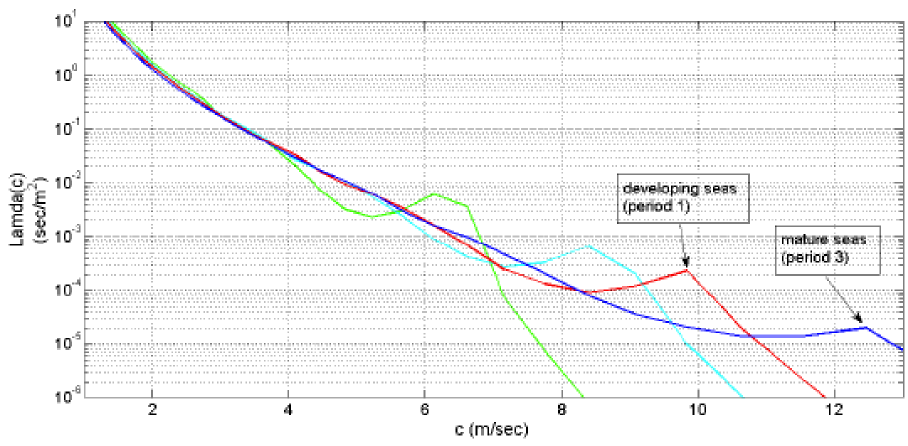

Figure 6. Computed evolution of the normalized spectral density of breaking crest length/unit area (Λ) against the wave speed c at different stages of wave development. The results for the developing wind sea (period 1) and mature seas (period 3) are indicated, and may be compared with Figure 7 . The enhanced Λ level at the evolving spectral peak tends to disappear towards full development.

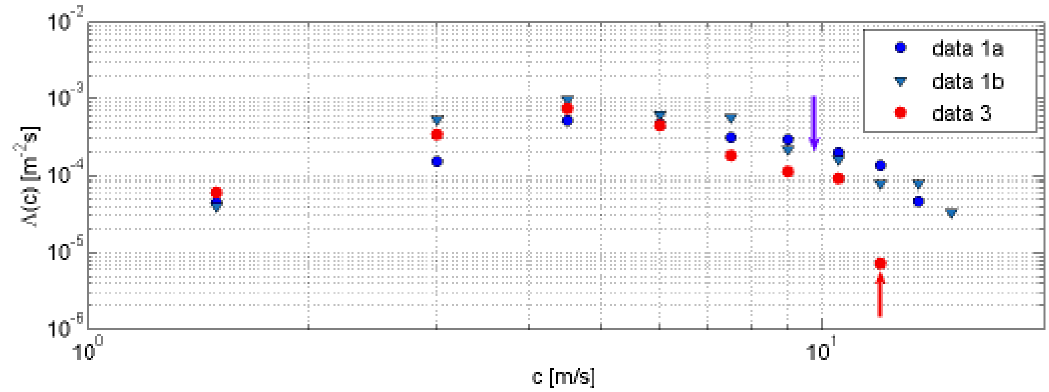

Figure 7. Measured breaking wave crest length spectral density Λ(c) for period 1 (blue circles and triangles) and period 3 (red circles) during the evolution for U_{10} = 12 m/sec (Gemmrich, 2005). The red and blue arrows indicate the spectral peaks corresponding to the wave age conditions during periods 1 and 3, where the spectral peak wave speeds were 10 m/sec and 12.5 m/sec respectively.

Overall, these model results for forecasting 12 m/s wind speed wave spectra, including dominant wave breaking properties, are very encouraging. This will be described in greater detail in a manuscript currently in preparation (Banner and Morison, 2006). This model has recently been tested at *hurricane* wind speeds up to 60 m/s.

We now show two aspects of our initial model runs at hurricane wind speeds of 45 m/s, where the model was found to run very stably. There was no retuning of any of the coefficients in moving from 12/ms to 45m/s. The first task was to compute the mean wave energy and peak frequency evolution curves. These are shown in Figure 8. It is seen that even at these extreme wind speeds, the evolution trends match the standard growth curves.

Figure 9 shows the inferred Λ(c) distributions for developing duration-limited hurricane wave conditions. These were calculated from equation (2) and assume the same value of b=2x10^{-5} that was used at 12m/s windspeeds. As the Λ(c) distribution is sensitive to the b value adopted, we caution that these values have significant uncertainty as we do not know how the value b changes when severe wind forcing is operative.

The other diagnostics as described above look very plausible, and we now look forward to performing model validations based on detailed comparison with the CBLAST Hurricane observations for wave spectral and breaking data.

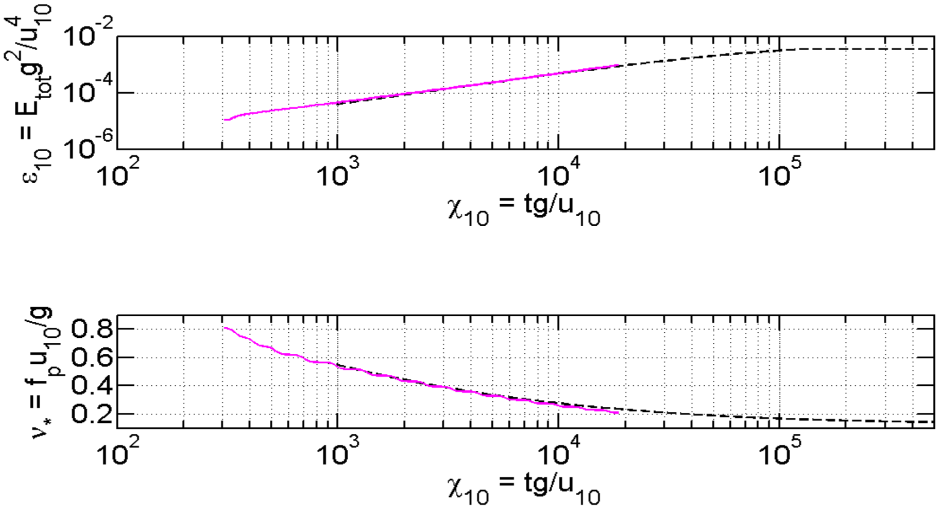

Figure 8. Evolution of the non-dimensional wave energy (upper panel) and non-dimensional dominant wave frequency (lower panel) against non-dimensional time for forcing by a hurricane wind speed U_{10} = 45 m/s. The background dashed curve is the trend of available field observations collated by Young (1999).

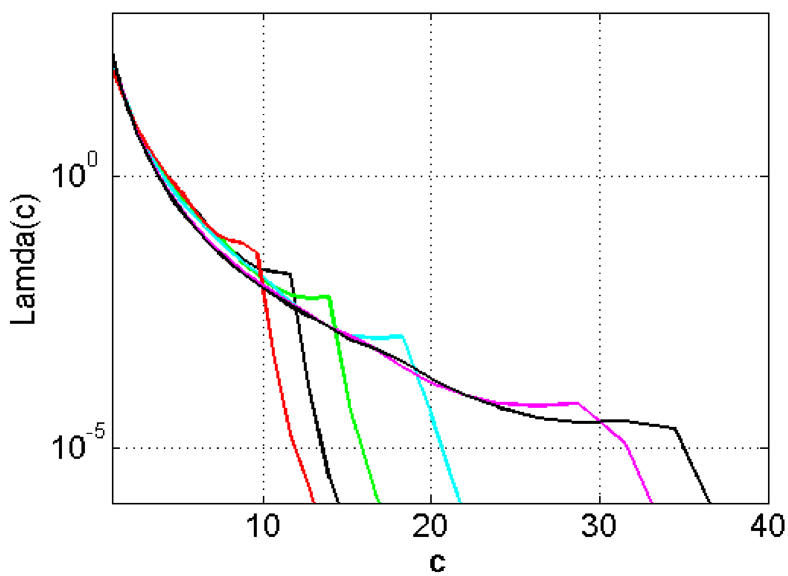

Figure 9. Computed evolution of the normalized spectral density of breaking crest length/unit area (Λ) against the wave speed c at different stages of wave development for U_{10}=45 m/s. The peak of the Λ(c) curves progress towards larger c values with time.

IMPACT/APPLICATIONS

Enhanced scientific understanding of severe sea state air-sea interfacial processes, particularly wave breaking and spray/droplet production rates, will provide more reliable parameterizations of these processes and closely related air-sea fluxes when introduced into operational forecast models. These improved parameterizations will increase the reliability of operational sea state and marine meteorological forecasts, especially during severe marine weather conditions. Of particular benefit will be the capability to provide routine forecasts of occurrence rate of dangerous breaking waves.

RELATED PROJECTS

The ONR project *Source Term Balance for Finite Depth Wind Waves* (Young, Banner and Donelan) includes a strong focus on the influence of steep waves and wave breaking on the wind input source function in strongly forced, constant depth, shallow water environments. This data set has been analyzed and initial papers on the methodology and results have appeared in refereed journals, with other papers in preparation [e.g. Donelan et al, 2004; Banner et al., 2005].

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